LIMIT SETTING AND OPTIMIZATION FOR NEW PARTICLE PRODUCTION AT CDF USING PHOTON TIMING

An Undergraduate Research Scholars Thesis

by

RANDY GLENN WHITE

Submitted to Honors and Undergraduate Research
Texas A&M University
in partial fulfillment of the requirements for the designation as

UNDERGRADUATE RESEARCH SCHOLAR

Approved by
Research Advisor: David Toback

May 2015

Major: Physics
Pure Mathematics

TABLE OF CONTENTS

ABSTRACT

Limit Setting and Optimization for New Particle Production at CDF using Photon Timing.
(May 2015)

Randy Glenn White
Department of Physics and Astronomy
Department of Mathematics
Texas A&M University

Research Advisor: Dr. David Toback
Department of Physics and Astronomy

New particles can be produced in high energy proton anti-proton collisions at the Fermi National Accelerator Laboratory (Fermilab). These new particles typically decay very quickly and their decay products can be recorded by the Collider Detector at Fermilab (CDF). In particular, the detector can measure the arrival times of photons produced in the decay of particles created in the interaction. Thus, we may be sensitive to the production of new, massive particles that decay in flight to photons. Such particles can be produced in versions of Supersymmetry, and even be produced as the decay of a Higgs boson. Since the photons that may have come from such events will arrive at the surface of the detector later than photons produced directly from a primary collision, they can be separated in time and analyzed for significance with a nanosecond timing resolution. This analysis is the optimization of the search for these new particles, and the final expected search sensitivity. The results will be the first of their kind, and are expected to set limits as a function of the mass and lifetime of the new particles.

ACKNOWLEDGMENTS

I would like to acknowledge Dave Toback for his continued support and mentoring through this whole process. I can't imagine a better PI or mentor. He has been so supportive and eager to help me grow as a person and as a researcher. Dave's instruction has made me able to do and go places I couldn't have imagined were possible. His devotion to his students and their futures is truly way beyond what is required of professors. The way that he has incorporated me and other undergraduates into high caliber research so early in our education has been crucial to the success we have had. I am so inspired by example he has set as a professor and as a researcher that I have decided to follow the path same into academia. I can only hope that one day I can be the kind of mentor and advisor that he has been for me.

I would also like to acknowledge the many previous students who's work when into the foundation and framework that this analysis was built on, including: Peter Wagner, Johnathan Asaadi, Adam Aurisano, Daniel Cruz, Jason Nett, Ziqing Hong and Vaikunth Thukral.

NOMENCLATURE

CDF	Collider Detector at FermiLab
EM	Electromagnetic
SM	Standard Model
SUSY	Supersymmetry
MSSM	Minimal Supersymmetric Model
GMSB	Gauge Mediated Symmetry Breaking
LNG	Light Neutralino and Gravitino
LSP	Lightest Supersymmetric Particle
NLSP	Next to Lightest Supersymmetric Particle
MC	Monte Carlo
COT	Central Outer Tracker
CEM	Central ElectroMagnetic Calorimeter

CHAPTER I

INTRODUCTION

Over the last century we have made incredible progress in our understanding of the true building blocks of our universe. The discovery of the electron, followed by the proton and neutron later on, has lead us on the path towards what is now the modern field of Particle Physics. The field has been deeply rooted with the goal to understand and discover all the particles that together build this world. Particle physicists have been motivated by this goal to build the huge collaborations and advance the technology to where we are now. This hard work has been richly rewarded with the large amount of discoveries in the 20^{th} century and the construction of the Standard Model (SM), which stands as our best understanding of the fundamental particles. Much of the workings or events of this world have explanations within the SM, but there are still questions to be answered and many unexplained phenomena that may be woven into the fundamental structure of the universe.

Some of the most notable phenomena that are currently being studied to complete the standard model are neutrino oscillations, the Higgs Boson's properties, and the existence of Dark Matter [1][2][3]. All of these pursuits could point to the existence of more fundamental particles and interactions between them that the SM doesn't predict. The important two of these towards our pursuits at CDF are the Higgs and Dark Matter. The Higgs Boson sits right on the edge of possibility for new physics, for it could have a place in the SM if its properties are one way and be the gate way to Supersymmetric models if its properties are found to be another way. One of the notable benefits to the SUSY theories is that they provide a simple solution to the hierarchy problem using cancelation terms to allow for the convergence of the Higgs mass calculations [2]. Additionally these models can provide prime candidates for the Dark Matter particle, in that some of these SUSY particles would be prevented from decaying by conservation laws, allowing them be produced in copious amounts in the early universe and still exist today[4]. If this were to be true, it is reasonable to hypothesis that high enough energy interactions in the laboratory could create these particles.

An important instrument in exploring the subatomic world is the particle collider. Through multiple generations of colliders before them, we have arrived at today's Tevatron and LHC colliders used by the CDF, D0, CMS, and ATLAS collaborations. Each of these has been designed to identify the signatures specific to the particles we have yet to observe experimentally. After collecting data for many years, both of these colliders have shut off (the LHC for an upgrade and the Tevatron for good) while the analysis and research continues. In this thesis we use is the data taken by the Collider Detector at Fermilab or CDF experiment (described in more detail in Chapter 2) during its Run II data taking period. Of particular importance is that after Run I the CDF detector was given a special modification with the instillation of an timing system into the electromagnetic calorimeter [5] . This whole system was designed and installed by the research group here at Texas A&M that I am now a part of. With it we are able to determine the arrival time of particle that interact with the EM calorimeters. Using this we will present and analysis that uses photons that arrive delayed to the detector to search for the creation of new particles.

I.1 Theoretical Motivations

As mentioned before there are many questions that the theory Supersymmetry (SUSY) could answer. The complication comes in that there are many versions of SUSY, and even the Minimal Supersymmetric Standar Model (MSSM) which encompasses many variations [6]. The one we choose to focus on a Gauge Mediated Supersymmetry Breaking (GMBS) version for its implications on the decays of the lightest SUSY particles and for providing a good candidate for warm Dark Matter [7]. In some versions of this model some versions [**?**], we would expect only the creation of both the Lightest (the Gravitino, the Supersymmetric partner of the as-yet-to-be-observed Graviton) and the Next-to-Lightest Supersymmetric Particles (expected to be a Neutralino, which is mostly the Supersymmetric partner of the photon - or Photino) to be produced at colliders today (which is why they have not previously been discovered at LEP, the Tevatron or the LHC). We call this the Light Neutralino and Gravitino (LNG) model. For our analysis we look at this interaction in the form shown in Fig.I.1, where a pair of neutralinos, Next-to-Lightest Supersymmetric Particles (NLSP), each decay in flight to a photon and a gravitino (LSP) [8].

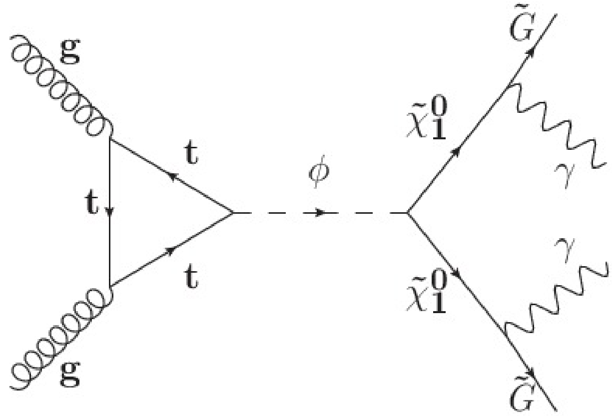


Fig. I.1. In high energy collisions between protons and anti-protons some GMSB models predict the production of SUSY particles from the decay of a higgs-like scalar (φ). This interaction would produce as shown two neutralinos ($\widetilde{\chi}_1^0$'s) with high probability. The subsequent decay of these neutralinos will each produce a photon (γ) the particle of light, and a gravitino ($\widetilde{G}$) seen as MET ($\not{E}_T$) [2].

Now it is important to note that there is reason to believe that we only need to consider the scenario where the $\widetilde{\chi}_1^0$ is long-lived, with a lifetime on the order of a few nanoseconds, coming from a heavy neutral scalar (φ) [9][10]. One such reason is that the coupling between the $\widetilde{\chi}_1^0$ and the $\widetilde{G}$ is weak due to the nature of gravitational interactions. Using this fact we can see that this predicts a signal that can be described as $\gamma_{\mathrm{delayed}} + \not{E}_T$(Missing Transverse Energy or MET). This is a very unique signal, which motivates a search for evidence of this LNG model. Moreover, little has ever been done with setting limits on these LNG models, because without a timing system these delayed photons will be inseparable from the backgrounds. Overall this model could have implications on how we may discover SUSY, motivating our analysis and search for long-lived neutral particles that decay to photons.

I.2 Overview of the Analysis

In this thesis we present the nearly final stages of the search for the production of a new heavy scaler, denoted as φ (as in Figure I.1), which decay to a pair of neutralinos each with a nanosecond lifetime. We note at the outset, that since the analysis is not complete, this document will focus on the analysis methods, in particular the description of the analysis, our methods to optimize it and our expected sensitivity. The central piece of experimental apparatus is the timing system that measures the time of arrival of a photon a the face of the detector. We will use this time to construct a new variable that we use to distinguish photons that would be considered ‘delayed’ and have possible come from the decay of a neutralino. We can do a quantitative analysis on just how delayed photons are in the data and see how that matches up with what we model for our signal.

This analysis has been in the works for many years over which it has gone through many iterations and steps. We will try to quickly describe these as we go through the first few chapters. Chapter II will discus the experiment and the timing system briefly, to give a set up to the work that has made the entire analysis possible. Next chapter 3 will go into the signal modeling and how to describe the $\gamma_{\text{delayed}} + \not\!\!E_T$ events. We will conclude the work done prior to me in with the data analysis and background discussion in the start of Chapter IV. What we are doing here is gathering the pieces of information we need to construct cross section limits. The formula we will end up using has the form $N^{95} = A * L * \sigma^{95}$ where N^{95} a limit on the number of signal events, L is the luminosity or amount of data, σ^{95} a cross section limit, and A is the acceptance. All of these will be discussed at length in their respective chapters, but this equation gives a structure to the way the thesis will progress. In Chapter 3 we discuss the signal and calculate what we need to achieve an N^{95} limit. Chapter 4 covers the simulations and process to calculate the acceptances. The luminosity is also discussed with the data analysis here, but will be a fixed constant. This gives us all the components needed to set limits in Chapter 5.

The work that we will present from there forward is the work to set limits on the signal process and extract the significance within these final results. We seek to set what are called cross section limits, which are an upper bound on the likelihood an event was occurring and our analysis wouldn’t be sensitive to it. These limits are dependent on the model parameters, so we will look at the functions of the 3 natural parameters that directly affect I.1. These are the mass of the scalar Phi, mass of the Neutralino, and lifetime of the Neutralino. What we expect to find for the final results of these limits and significance and how they impact the search for new particles at CDF will be presented as the conclusion of this thesis.

CHAPTER II

THE EXPERIMENT

This chapter will walk through the relevant details about the design and functionality of the experiment. We will discuss the Tevatron collider, the CDF detector, and then the EMTiming System that makes our analysis possible.

II.1 The Tevatron

We begin with the discussion of the largest component of this experiment, the collider. The Fermilab Tevatron is a proton-antiproton collider with a center of mass energy of $\sqrt{1.96}$ TeV and a radius of 1km. The ring is situated bellow ground at Fermilab but can bee seen in Fig. II.1. A complete description of it and its operations in [11][12][13], but put simply it uses superconducting magnets to steer beams of protons and antiprotons in opposite directions around the accelerator. These beams are directed to cross at the two main collision halls where the CDF and D0 detectors are situated. The detector our data comes from is the CDF Detector and we will discuss its operation in detail next.

II.2 The CDF Detector

The CDF or Collider Detector at Fermilab is situated in the collision hall B0 on the Tevatron ring. Its design is that of a general purpose detector, giving it the strength of being useful for many different analyses. The detector was built to be symmetric around the mean collision point, with symmetries in the azimuthal and radial directions. The detector consists of many layers or shells to be sensitive to all types of decay products produced in the interaction. A detailed description can be found at [12].

At the center there are the Tracking systems designed to pinpoint the tracks and vertices made by charged particles as they leave the collision point. Added by the collaboration of the silicon detector and central outer tracker (COT), the CDF detector records accurate positioning and timing

Fig. II.1. Arial view of the Fermilab site with a clear view of the ring next to Wilson Hall (which is the tall building in the foreground). The Tevatron sits underground just outside of the service road shown here. There are two places the beams are brought to collide called the Collision halls. There aren't distinguishable in this picture but there is one on the close side housing the CDF detector and one on the far side housing the D0 detector.[14]

for the particles created in the interaction. This data was important to allow analyses like ours to be possible. We use it for many of the early steps in this analysis, such as a way to distinguish the photon hits in the calorimeter from electrons and determine the collision time to reference against.

At the next layer just outside the COT there is the Electromagnetic or EM Calorimeter. This system is responsible for detecting and measuring the Electromagnetic hits in the detector caused by electrons and photons. These energy deposits can look very similar at this stage, but together with the other system we can distinguish photons, electrons, and any other hits in the calorimeter. Overall this system is extremely crucial to our analysis and a more detailed description of its operation can be found in [16].

The last two parts of the detector play little role in our analysis, but are crucial in the operation of the detector. The Hadronic Calorimeter is responsible for measuring the energy deposited by hadrons, particles that consist of quarks. Outside of that are the large muon detection chambers. Muons are much less likely to interact and having a larger system designed measure them allows

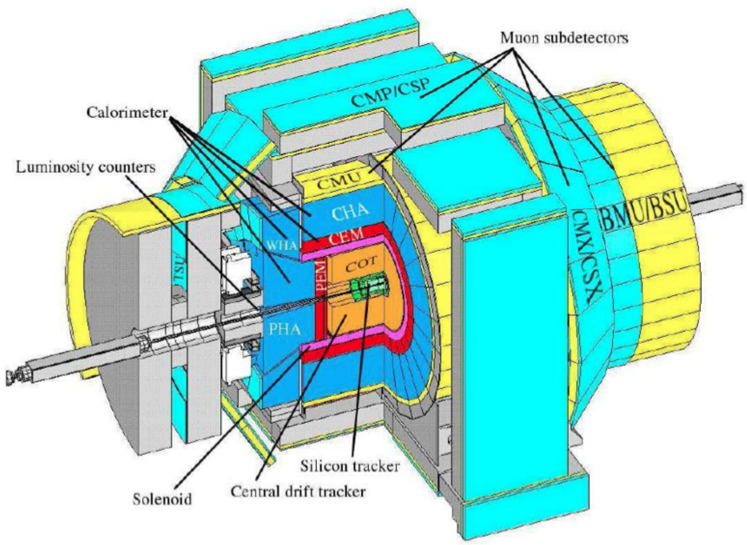


Fig. II.2. A diagram of the CDF detector showing some basic sectioning of the detector. Labeled are the different detector elements including the trackers, calorimeters and muon detectors. Our analysis has heavy use of the tracking and EM calorimeters. [15]

for the most accurate measurements. With these last two systems the detector now has all the information to reconstruct almost all that occurred in the interaction.

II.3 The EMTiming System

Finally the piece to the CDF Experiment that makes this analysis possible is the EMTiming System which is described in more detail in [5] and shown in II.3. With this system we can track the times of arrival of every particle tha tdeposits a significant amount of energy in the the EM Calorimeter. This allows far an additional final collision point time in the events and allow us to do this search for delayed photons that are the crucial signiture that allows us to distinguish signal events from the backgrounds in a timing distribution.

The system consists of multiple layers of physical hard boards installed both on the back of the calorimeter and in the processing hardware away from the detector. It operates by duplicating the signal from the photo-multiplier tubes or PMT's and collects them all as it sends the signals back

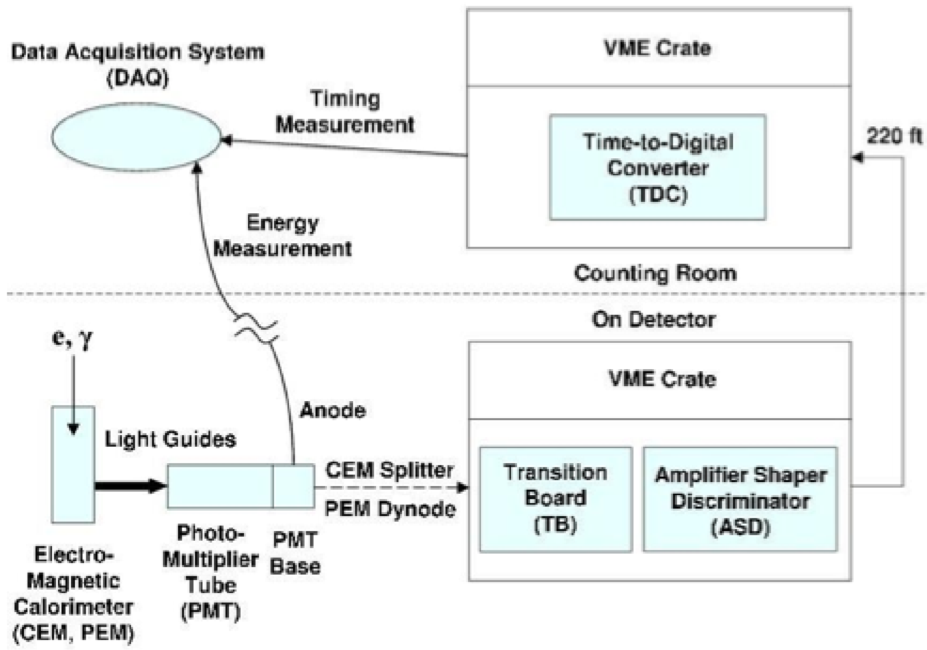


Fig. II.3. Shown here is a schematic of how the EMTiming system is connected into the calorimeters and triggers a timing measurement that is stored with all the other measurements of the interaction. The time given here is taken relative the time of collision given by the tracking system and is stored for every hit in the EM Calorimeter. [5]

to the DAQ where the times, relative to the mean collision time, are recorded. It is the use of this information that makes our analysis so powerful and unique.

CHAPTER III

SIGNAL MODELING

Signal modeling is a crucial step in every analysis. There was extensive work put in over multiple years for this analysis to validate and model the events that we call signal. The following sections are a summary of the results of that work, for complete descriptions go to the previous publications such as [17].

Specifically we used a program PGS that is an overlay to the typical Pythia Generator for particle physics [20]. We use this program to give us a very large set of Monte Carlo simulated data at a particular set of values that we can use analyze the Signal shape

III.1 Overview of the Simulations

To understand what events from new particles would look like, we do Monte Carlo (MC) simulations of both the physics process as well as how the final state particles interact with the detector (and its response). The physics is simulated with the PYTHIA MC, and we use two different detectors simulations to be described later. The simulation begins with the production of a heavy neutral scalar φ and then decays. Sinceit will decay into a pair of neutralinos, the mass of the phi will play an important factor in the kinematics of the produced neutralino and the subsequent signal photon. For the moment we will take the general scalar to be higgs like at two different masses (125 GeV and 200 GeV) to see how our analysis sensitivity changes as a function of its mass.

The analysis can be thought of as a selection requirements (for events to pass our final selection requirements), but the timing distribution will help us distinguish between signal and backgrounds. In addition, as we will see, many different values of the $M_{\varphi},\ M_{\widetilde{\chi}_1^0},\ and\ \tau_{\widetilde{\chi}_1^0}$(Mass of the Phi, Mass of the Neutralino, and Lifetime of the Neutralino) will produce different kinematics (acceptances) and timing distributions. As it will be useful, we think of the discussion of the signal, as well as the data or backgrounds, in terms of a timing distribution. For this we construct a variable that isn't just the time of the arrival of the photon at the calorimeter, but rather make an estimate of the timing delay a photon has relative to the collision time. We call this variable Δt and it is defined by the equation:

$$\Delta t \equiv (t_f - t_i) - \frac{|\vec{x}_f - \vec{x}_i|}{c} \tag{III.1}$$

This equation shows has two key factors lying just under the surface. It causes the analysis to be closely related to the geometry with the time-of-flight calculation for the photon. This also will indirectly account for the kinematics of the process through the effect of conservation of momentum. In a decay such as this the energy of the neutralino strongly defines how confined the photon is to the direction of travel of the neutralino. This effect is called boosting and will correlate to much shorter delay times. For our best result we want a relatively slow moving neutralino that will decay as shown in Figure III.1. For a more complete description of the issues that determine the Δt distribution, see [9].

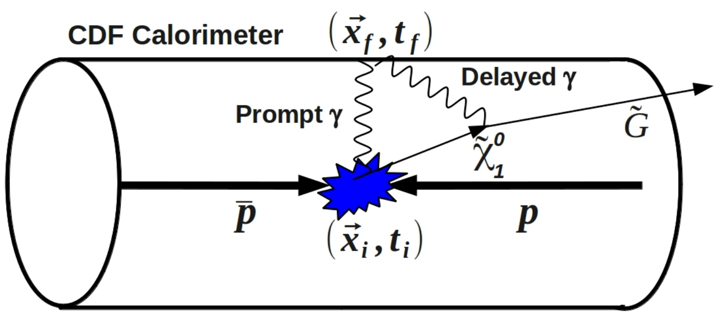


Fig. III.1. An example of the production of a long lived neutralino that decays into a photon and a Gravitino. The figure shows that the process allows our signal to be distinguishable from the backgrounds. The non-negligible lifetime of the neutralino and the increased time of flight, the photon will arrive later than a photon produced in the primary collision. [18]

III.2 Event Selection Criteria

In order to discuss signal events we must first define what it means to be considered a signal event for this analysis. We use a set of selection requirements to narrow down to the set of events that are good for this analysis. The list of these requirements is given in III.1 and III.2 and have been developed over the years for previous versions of the analysis. Since we are interested in single phi production and decay, we will consider events that have a single photon and MET (Missing Transverse Energy) for the reasons described in [9]. The event identification requirements are designed to reject the large number of backgrounds to our signal, and ensure a sample of events which can be expected to be well measured. The first table gives what are typically called the ID cuts, which are tweaked slightly for this analysis due to the focus exclusively on photons. Second is the afore mentioned selection requirements on events. Particles matching the qualities in III.1 are called good photons, while the events matching the requirements in III.2 are called $\gamma + \not\!\!E_T$ events.

Quantity	**Selection Cut**
EM cluster E_T^0	1 cluster with $E_T^0 > 30$ GeV
Fiducial	$\lvert X_{\text{CES}}\rvert < 21$ cm and $9 < \lvert Z_{\text{CES}}\rvert < 230$ cm
Hadronic fraction	$\frac{E_{\text{Had}}}{E_{\text{EM}}} < 0.125$ $E_{\text{Had}} > -0.3 + 0.008 \cdot E_{\text{T}}^0$*
Energy isolation	$E_{\text{cone }0.4}^{\text{iso}} < 2.0 + 0.02 \cdot (E_T^0 - 20.0)$
1st CES cluster energy	CES $E > 10$ GeV* CES $E/E > 0.2$*
2nd CES cluster energy (if one exists)	CES $E^{\text{2nd}} < 2.4 + 0.01 \cdot E_T^0$
PMT spike rejection	$A_{\text{PMT}} = \frac{\lvert E_{\text{PMT1}} - E_{\text{PMT2}}\rvert}{E_{\text{PMT1}} + E_{\text{PMT2}}} < 0.6$*
Track Multiplicity	Number of N3D tracks either 0 or 1
Track P_T	If $N3D = 1 \rightarrow P_T < 1.0 + 0.005 \cdot E_T^0$

Table III.1
Shown here are the quality event selection requirements used to identify a good photon [18]. These requirements help ensure that events passing the criteria are mostly likely photons and will be useful in our analysis. Additionally, these cuts give us an uniformity when analyzing data and simulation since they are applied to both.

The set of phi events that would pass out set of selection requirements define what our signal events would look like. Any events that qualify as $\gamma + \not\!\!E_T$ events that come from the decay of a Neutralino are called signal. This is a term that is used to isolate what is being searched for. In almost every

Quantity	**Selection Cut**
Trigger (applied to data only)	`WNOTRACK`
Good photon passing the ID cuts in Table III.1	$E_T > 45$ GeV
$\not\!\!E_T$ $(z = 0)$	> 45 GeV
Standard Beam Halo Rejection	Reject event if the cluster has 9 or more hits in the same wedge, or has 2 or more hadronic tower hits associated
Standard Cosmic Ray Rejection	$\Delta\phi(\gamma,$ closest muon stub$) > 30$ degrees
Track veto	$P_T > 10$ GeV NCotAxSeg(5)≥ 2 $\frac{\text{COT \# HitsTotal}}{\text{COT LastLayer} + 1} > 0.6$
Veto on any jet not identified as the leading photon	$E_T > 15$ GeV
Large standard vertex $\lvert z \rvert$ veto	$\lvert z \rvert < 60.0$ cm for all identified standard vertices
Electron rejection veto	$\Delta R_{\text{pull}} > 5.0$
Vertex selection	Require at least one spacetime vertex with: $\Sigma P_T > 5.0$ GeV $\lvert Z_0 \rvert < 60.0$ cm $N_{\text{Tracks}} \geq 3$

Table III.2

The set of requirements that define an Exclusive $\gamma + \not\!\!E_T$ sample [18] for both data and Monte Carlo, these cuts are use to identify good isolated events for this analysis. Events passing all of these are believed to have an exclusive well constructed photon and a large about of missing energy, which are a signiture of I.1. datasets.

case the underlying event that you would be looking for is not directly detectable. One must define the criteria that helps to isolate the signature of the decay of the particle or particles that they are searching for.

Now that we have a good handle on how the data is affected by the quality requirements we have to look at what percentage of actually signal events we expect to make it through to the final sample. This value is called the Acceptance and found one again with simulated events that replicate data. In these samples we can generate events that always contain the decay that we are searching for. With that we simply apply the same cuts like it is data. This is exactly as we were finding the Slope of the signal timing distribution, but this time we are interested in the fraction of the simulated events that are filling our sample.

We want to most closely replicate what is happening in the detector so that our estimations for the Acceptance introduces the smallest systematic error possible. To do this we use a program package called CDFsim that simulates the detector and how it would detect the particles that the generator simulates. This package allows us to very accurately and with high confidence generate events that would be the closest looking to data as possibledue to the simulation speed and the volume of the output data. The issue comes in that it is not feasible to run all the values we need to do a search and exploration of a large parameter space. That is why we bring back PGS and are seeking to validate that the Acceptances given by each method are in close agreement. Shown in III.3 are very preliminary results from an early attempt.

These results are actually pretty promising. There is still work to be done and we seek to move to the higher mass to improve results. We will show later that our 125 GeV benchmark is in fact a bad region to be using, so the fact that all the percentages are on the right order is a good sign. The ultimate goal will be to show that the acceptances for these two simulations is same up to a scale factor at all points. What this will give us is confidence in the accuracy of the simpler generator, which turns out to be a very useful tool. This allows us to run calculations for a multitude of points relatively quickly, while maintaining high confidence in the fact that it still models the data reliably.

Cut	**PGS**	**CDFsim**
Central	14.78%	10.79%
ET $\geq$ 45GeV	2.30%	1.99%
MET $\geq$ 45GeV	1.53%	1.78%
Jet veto	1.15%	0.49%

Table III.3

The values shown here are were made in attempt validate the use of our simpler Simulation PGS. These are still preliminary numbers and due to the low statistics at the $125\ GeV$ Phi mass these have large statistical uncertainties. The goal is to have samples run with both simulations and count the percentages passing each selection requirement. Once we get reliable final results and at $200\ GeV$ then we can either validate or make a slight correction to PGS, allowing us to use only it to generate our used values.

The results that our PGS simulation gives us, by doing as before, many runs on different parameter values can be shown again as a mapping of each point in the parameter space to an acceptance value. We use the quality cuts on the Monte Carlo and simply count the resulting amount of events verses the starting amount. These results are shown in III.2 as a contour plot again over the same space that we had found the slope parameters in the last section.

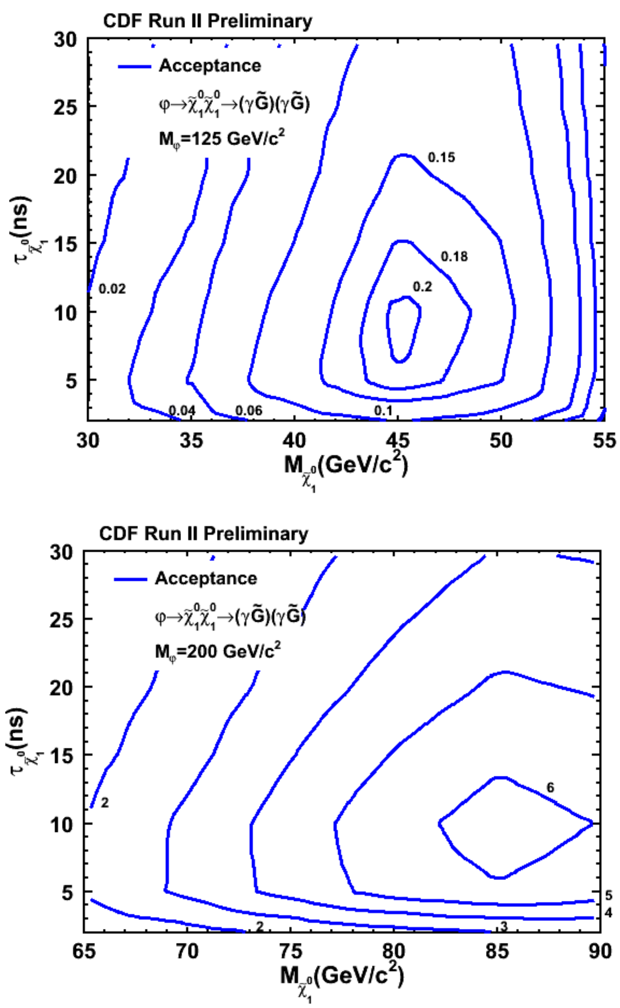


Fig. III.2. The acceptance values that we are using for the time being. Again there are versions here at a phi mass of 125 GeV and 200 GeV exploring our acceptance percentage for each area of the parameter space. There is a clear region of each where the acceptance peaks. The central region for the neutralino mass changes between them, but the lifetime region stays constant. This effect is almost entirely due to the kinematics of the decay.

One way to interpret these results is to just look at how the value for the acceptance goes up or down in the different directions. We can see central regions of both of these two plots where the acceptance is at a maximum. These regions must be favorable for producing a $\gamma + \not{E}_T$ signal with a large number of events with 2 ¡ Δt¡ 7ns. and therefore a large portion of events generated at these parameters will pass all the quality cuts to be in our sample. Translating that thought onto what it means for data is that in those regions of parameter values we are likely to have a larger percentage of any signal that is present make it into our final results. This translates to regions we would be more sensitive to with analysis, and assessing that sensitivity is the goal of this paper.

III.3 The Signal Shape and Slope Parameter

After all the event selection requirements the ensemble of events will have distribution as shown in III.3. As seen in that example, there are two components to the shape. The first is that the timing distribution at large times (well above the resolution of the detector) is an exponential. The left hand side shows just the resolution. Multiple studies have shown that this we always see this exponential shape, but that the value of the slope depends on the mass and lifetime parameters [9][17][19].

One key point about this distribution is that the entire shape can be described by a single slope parameter that fits the function as shown in the figure above. This parameter we will call just as the Slope of the signal timing distribution. We will show later that we can determine this parameter for any value of the input parameters to our model. This is where we will bring in simulations into the picture to aid both in the speed at which we can compute needed pieces of the analysis and the modeling of a large amount of different values. This will become a powerful mechanism by which we can use to estimate our search sensitivity in a few chapters.

Now in order to move forward we wanted to assess how many different values for the mass and lifetime of the neutralino will affect the shape of the signal. As discussed before the different model parameters, the mass of the scalar, the mas of the neutralino, and the lifetime of the neutralino all affect the behavior of the signal. We can use simulation techniques to estimate what the decay of these would look like using given model parameters. Specifically we used a program PGS that is

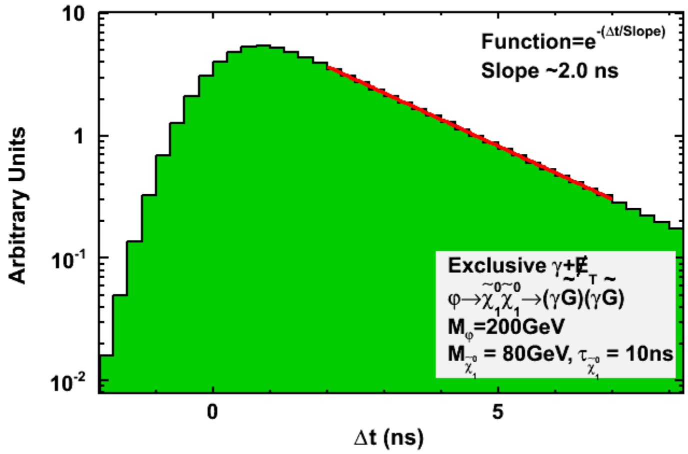
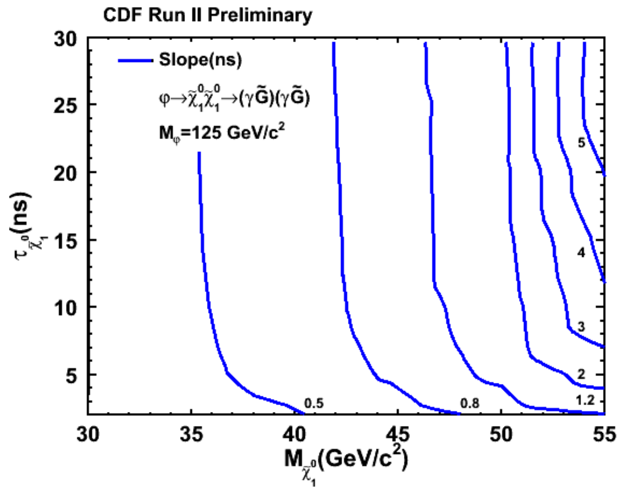


Fig. III.3. The distribution of events that match the signal requirements as a function of Δt. The falling exponential from the true Δt distribution is smeared by a Gaussian because of the resolution of the detector. This shape is fit within the signal region of 2-7ns for the slope parameter with the function given on the plot. We will use this parameter throughout the rest of the discussion to generalize the shape of our signal.

an overlay to the typical Pythia Generator for particle physics [20]. We use this program to give us a very large set of Monte Carlo simulated data at a particular set of values that we can use analyze the Signal shape. In particular we look at the delay times for the photons that result from the decay of the neutralinos. With this simulation we can make in essence a version of III.3 at any values of the input parameters $M_{\varphi},\ M_{\tilde{\chi}_1^0},\ and\ \tau_{\tilde{\chi}_1^0}$ (Mass of the Phi, Mass of the Neutralino, and Lifetime of the Neutralino.)

The goal of this is to fit each of these as a falling exponential as shown above. This allows us to find a Slope parameter for any value of the input parameters. Effectively giving us a way to translate from our 3 input parameters into just one that tells us everything we need about the timing distribution the signal would take. This produces a mapping that we will use over and over in this analysis. The results of this are shown in Figure III.4 as a contour plot of the slope parameters over a chosen subset of the parameter space.



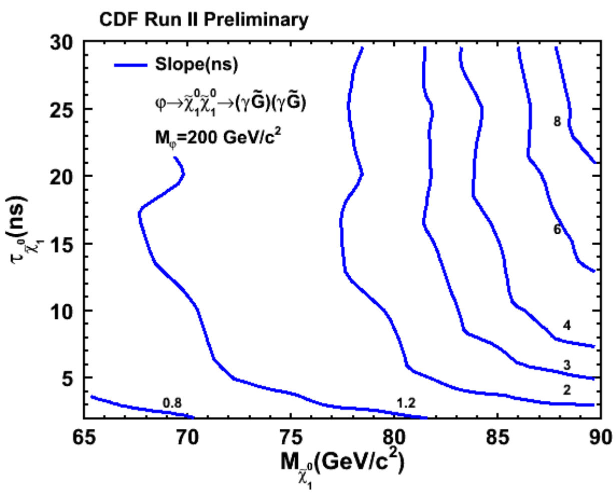


Fig. III.4. Contour plots that show the value of the slope parameter as a function of masses and lifetimes. For the first example we have again fixed the scalar phi mass at $125\ GeV$. The second is at the mass of $200\ GeV$. The reason for both will become important later. Whats important here is that we have a defined value at every point and a mapping from those values directly to a signal shape. We will use these values and method of plotting throughout the rest of the analysis.

CHAPTER IV

DATA ANALYSIS AND BACKGROUNDS

Now that we understand the signal and have a way to model the timing distributions as functions of our Δt delay time we can move on to discussing the data and backgrounds. With that understanding we can get to the next crucial piece to being able set limits, the Acceptance. The discussions in this chapter will mainly be a summary of work that is already published and an overview to what will get published as a part of the full data set analysis soon. That being said, the values and plots shown are good indications of what we believe the final results to look like.

IV.1 Data Analysis and Event Selection

Up to this point we have only really discussed simulations and models for how we believe the signal events will look. Now we must open the box a little and start looking at how the data, and the expected backgrounds, actually looks. The data we have used in this analysis is from the first part of the CDF Run II data set. Most of the results to be shown here in this thesis will be only using the first $6.5fb^{-1}$ of the data, we are in the process of migrating to the final and full $10fb^{-1}$ data set now. What this means is that these results are still preliminary as far as our final analysis goes.

The data from the CDF detector at the Tevatron comes in as millions upon millions of events. Each event contains record every output signal from the detector, how much energy was deposited in what piece of the detector, where the vertices are, what tracks were left, and much more. With all this information you can reconstruct the nearly everything that happened in the event. The task of any analysis is to put restrictions and cuts on what you want to have seen in the events. This allows you to focus in on events with certain signature and events that match the qualities that are good for your analysis. For example our analysis has requirements that only let through events that we can use to distinguish between the just background and background plus signal hypothesis using the high energy delayed photon.

Our quality requirements for the $\gamma_{\text{delayed}} + \not{E}_T$ sample were discussed in the previous section in III.1 and III.2. These requirements are also applied to the data with the slight additions as mentioned, since some requirements can only apply to data and not Monte Carlo. What is important with these before we accept and move on with them as knowing how they affect the data and sample size. If there are too few events left at the end of your cuts then you are being too restrictive and your results will have very low statistics and therefore very large room for error. What we do to assess this is make what is called an even reduction table and see how each cut affects the number of events. Shown in IV.1 is what ours looked like on the $6.5fb^{-1}$ data set.

Requirement	**Number of Events**
Central photon with $E_T^0 > 45$ GeV, $\not{E}_T^0 > 45$ GeV and passing trigger requirements	38,291
Beam halo veto	36,764
Cosmics veto	24,462
Track veto	16,831
Jet veto	12,708
Large $\|Z\|$ vertex veto	11,702
$e \to \gamma_{\text{Fake}}$ veto	10,363
Good vertex events	5,421

Table IV.1
The event reduction table for the first $6.3\ pb^{-1}$ of data from the CDF detector. Shown are the numbe of events that satisfy each subsequent requirement are narrowed down [18]. These numbers are used from the previous dataset, as our results for the full data set are still being processed. It is important to remember that these events being narrowed down to fill the $\gamma + \not{E}_T$ sample that is the sum of all that is happening in the data. Therefore it could be only backgrounds or include some percentage of signal.

IV.2 Backgrounds to the Search

The backgorunds, and the estimation of their rates as a function of time, are described in detail in [18]. To summarize there are only from 3 distinct sources that we will group based on timing signature and can be directly estimated from the data as shown in Figure IV.1.

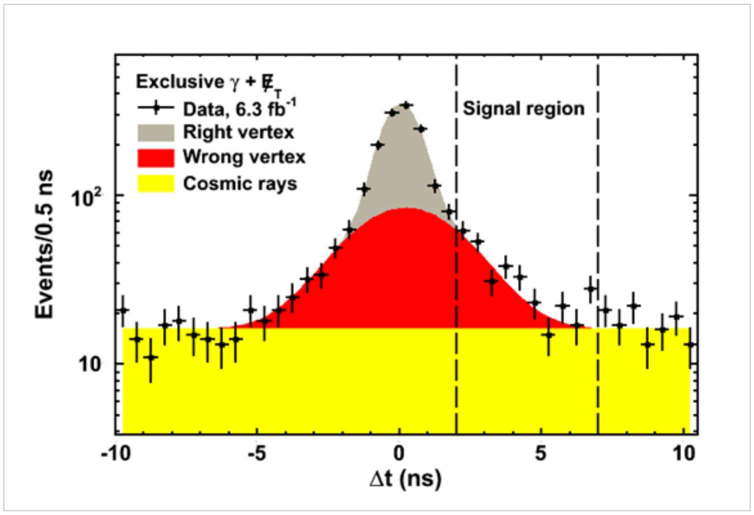


Fig. IV.1. This plot shows the distribution of events with the Exclusive $\gamma + \not{E}_T$ final state. The distributions are plotted with respect to there 'delayed' time (Δt) in nanoseconds. There 3 clear background distributions each accounting for one of the different shapes that the backgrounds can take and are scaled using a Control Region [19]. This data driven background estimation method allows us to predict what the backgrounds for the positive delay times will be using the negative delay times. This plot was published in [20]. And there is clearly no evidence for new physics.

As a brief working understanding of these backgrounds we must think only about their distributions in time. The Right Vertex distribution, drawn in gray, accounts for the resolution of the detector being 0.65ns and is the photons that were properly matched to an initial point and correctly calculated with III.1. The second, Wrong Vertex, background accounts for the wider distribution in time (resolution of about 2ns) for photons that were improperly picked and is not correctly calculated with III.1. This distinction is important as the 2 separate distributions it leads to are very different. Lastly, the Cosmics is a roughly flat distribution that has nothing to do with the collision and is from sources outside the detector.

The backgrounds are well understood in this analysis, but due to the statistical nature of particle collisions and creation it would be impossible to predict the exact number. It is for this reason that we have done a data-driven background estimation. For this we use a control region in which there would be no signal contribution, such as the negative delay time region ($-7\ -\ 2\ ns$), in order

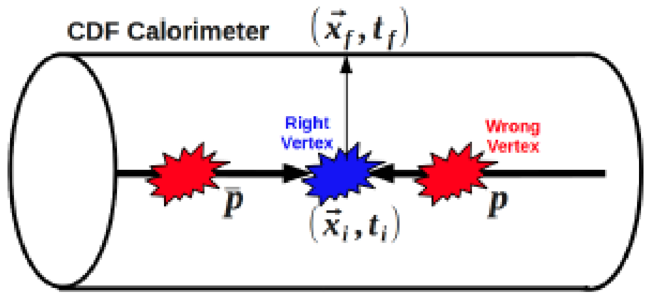


Fig. IV.2. Just as described before the Δt equation can be caused to give an incorrect value if the initial point is choosen wrong. This gives rise to the two distributions for the backgrounds called Right Vertex and Wrong Vertex. [18]

to estimate the positive decay time region. This is how we scale our background distributions and gives us the ability to look for an excess in the Signal Region. To show what Signal would appear as in this distribution we have plotted the distributions all on top of each other in IV.3.

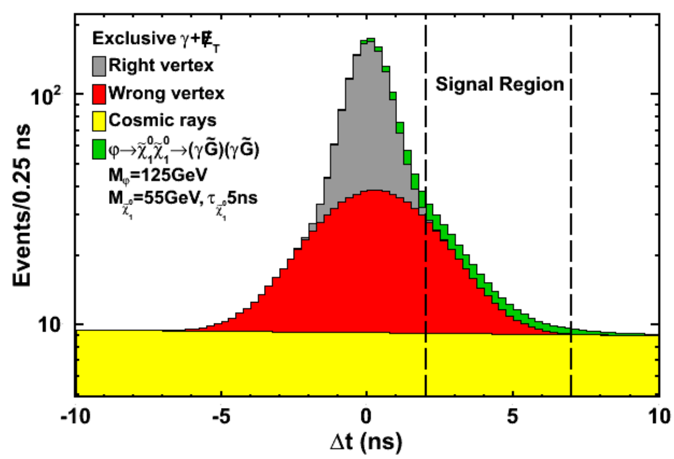


Fig. IV.3. The estimated backgrounds for our new dataset and plotted with the expected shape of the signal distribution would appear as on top of the backgrounds. The signal shape is in fact the shape shown in III.3. The falling exponential draws the weight of the distribution to the positive side and into our signal region.

CHAPTER V

EXPECTED SENSITIVITIES AND LIMIT SETTING

We now have all the pieces we need to tackle the meat of what is new to this analysis, the limit setting and expected sensitivities. The goal with these limits is first assess the amount of signal that could be in the data as a function of the signal shape. Then from there we can construct our final cross section limits, which by design will be a function of the model parameters $M_{\varphi},\ M_{\widetilde{\chi}_1^0},\ and\ \tau_{\widetilde{\chi}_1^0}$ again.

V.1 Overview of the Search Sensitivity and Estimation Methods

Before showing or discussing values we need to discuss how to interpret the analysis sensitivity which we will estimate to be equal to the expected limits we might set in the event that there is no new physics in our data. For this we need to first define a set of terms and establish an equation that will be used to evaluate our final results, which are called 95% confidence limits on the cross section of the process. To start with, it needs to be known that a cross section is the probability or likelihood of a process/decay occurring. Then we build up to that a 95% confidence limit on a cross section is the largest probability for by which if the true value were any greater we would have detected it, at 95% certainty. So my setting limits on the cross section we are able to say at what likelihoods we would have seen, or been sensitive to the production of the particle.

Our first stepping-stone to this will be simple limit is to start with the estimation of the rate at which new particles would be produced. This is given by $N^{95} = \sigma^{95} * L * A$. This is in fact the afore mentioned upper limit on the number of signal events that could be in the data on top of the background. These events will fit the shapes we described back in Section III. These will be found using our limit program and will be described first. But to look ahead we will need the equation below.

$$\sigma^{95} = \frac{N^{95}}{A * L} \tag{V.1}$$

In this equation A is the Acceptance and L is the total Integrated Luminosity (amount of data). So in fact this formula is quite simple in construction, that the cross section is equal to the number of events divided by the total events times the Acceptance percentage. With this last tool we are now ready to actually evaluate our limits and start searching for where we might have sensitivity.

V.2 Setting Limits

Many programs exist for setting limits, we chose to use a program called MCLimit (CDF 8128). Since there are a number of different timing distributions, said differently there is a different slope for many different mass/lifetime combinations, it is is appropriate to estimate our sensitivity as a function of the slope. For this we construct the total background timing distribution to go along side the signal and data timing distributions. We then allow the program to run an iterative process to find the scaling of the signal distributions allowed with the backgrounds and data. The return of this program is a specific N^{95} value for each slope parameter input. and is shown here in V.1.

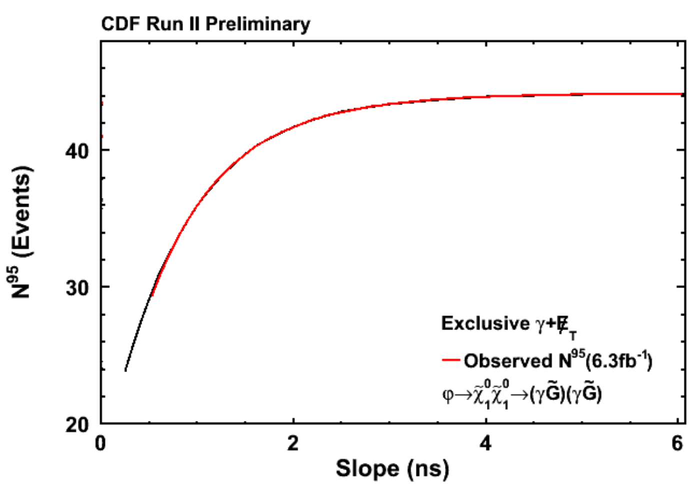


Fig. V.1. The distribution of the Observed N^{95} limit run with different signal distribution shapes, as described by there slope parameter. These values were found for the old data set but are a good model for what the limits will be like for the full Run II data set. We use the equation that models this plot to translate any value for the slope into the N95 at that point. By this process we will move on and construct limits over the parameter spaces that we have built slopes and acceptances for.

V.3 Finding Expected Sensitivity Regions

Now that we have this result, we can fit the correlation for a functional form that gives us a mapping from a slope parameter to an N^{95} limit. Then have all we need to combine the Acceptance and Slope values found at each point in **??** and **??**. Our fit translates Slopes to N95, Acceptance is given, and the Luminosity is a constant which means that σ^{95} is defined for every point. This is shown in V.2.

There is clearly a dramatic difference in these limits, though elements of the general structure remained the same. We still have a central region at which the limits attain the best/minimal value. The largest difference is the values; our limits at the M_φ equal to 200 GeV are at least an order of magnitude better than 125. Another important feature is how the regions of highest sensitivity are both in the 5-10 ns lifetime region and is relatively stable under change. With those two features it is clear that maybe fixing the φ mass is the wrong way to look at these limits. Therefore will now keep fixed the lifetime of the neutralino fixed at 5ns where our limits appear optimal and attain V.3.

This plot tells us that we are exactly on the right track. As the mass of the phi increases our limits are quickly improving. The optimal region follows a previous result that predicted the kinematicly and theoretically favored value of the neutralino mass as a function of M_φ[21]. Overall these limits are convincing evidence that our analysis is quite effective and might be sensitive at higher masses. We will continue on and make the up dates to these given values with the full data set, but it is not expected that any change will be dramatic. It is for this reason that we continue on into the last section and hope to show the significance that these results under the assumption that they are a good model for what the full dataset results will be.

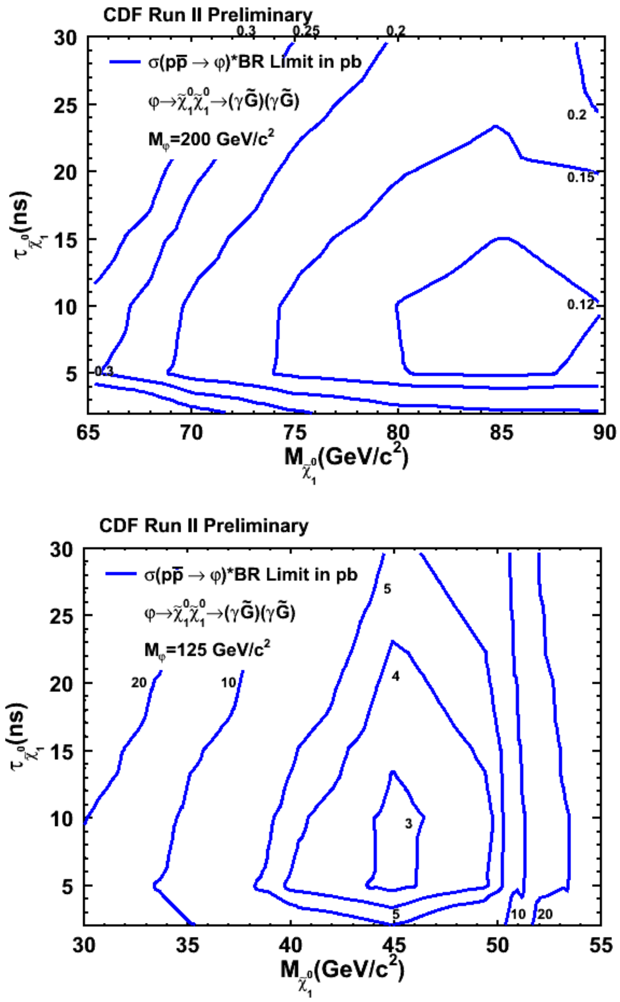


Fig. V.2. Expected cross section limits as a function of lifetime and mass. These are the limit on the likelihood of production of the neutralino were it to have the specific mass and lifetime, given the scalar φ mass. There is a version shown for each $125\ GeV$ and $200\ GeV$ again. As you can see limits are extremely improved when looking at a phi mass of $200\ GeV$. Note that the $125\ GeV$ case the limits fall off very quickly and dramatically.

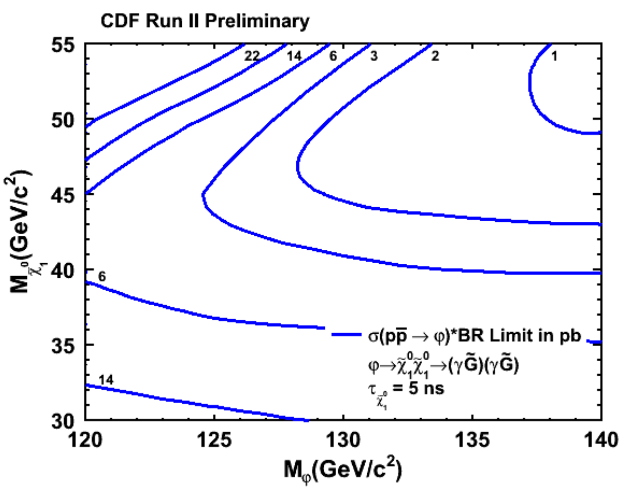


Fig. V.3. The expected sensitivity as a function of neutralino mass and phi mass. First is that it confirms that the kinematicly favored mass of the neutralino scales proportionally up with the mass of the Phi, which accounts for the upward trend of the best limits. Next is that our limits in fact improve as we look at increasing scalar phi masses. A version of this figure for higher masses is in progress.

CHAPTER VI

RESULTS AND CONCLUSIONS

Up to this point we constructed distributions that model our signal, found the acceptance our analysis has to these different distributions, and calculated expected cross section limits with these results. We now want to show what we are actually sensitive to in this analysis by comparing our limits with the production cross sections. The idea being here that if we know our cross section limits say we would be sensitive to the production if it was occurring at certain likelihoods dependent on the model parameters, then we can see were theory predicts such likelihoods.

VI.1 Sensitivity and Exploring Results

Sensitivity, being defined as where we would expect (at 95% confidence) to have seen statistically significant evidence of signal, is the ultimate goal of any analysis. If an analysis returns results and limits that are above predicted values then they have no impact on reducing possible values of the parameters and would need to increase its sensitivity. With our analysis we wish to find the regions that we might have sensitivity or how much more sensitive we would have to be to have seen something.

To quantitatively assess this we wish to define a quantity that tells us just how sensitive we are. We do this by taking the ratio of the cross section limit to the production cross section. This quantity will show us where we have sensitivity when we apply this to the Figure **??**. We have used an approximation scheme to estimate the production cross section that comes from Ref [21].

What can be seen here is that not only were our limits improving at higher masses, but we are in fact more sensitive in these regions. This motivated us to then see how this analysis would be sensitive if we extended out to φ masses of 200 GeV or even 300 GeV. We could see that our search is not sensitive to low mass or even higgs massed neutral scalars, but that didn't mean that we wouldn't be sensitive to them at much higher masses. In pursuit of that idea we wanted to see just how our sensitivity goes when pushed to higher masses. For simplicity we now fix two of the

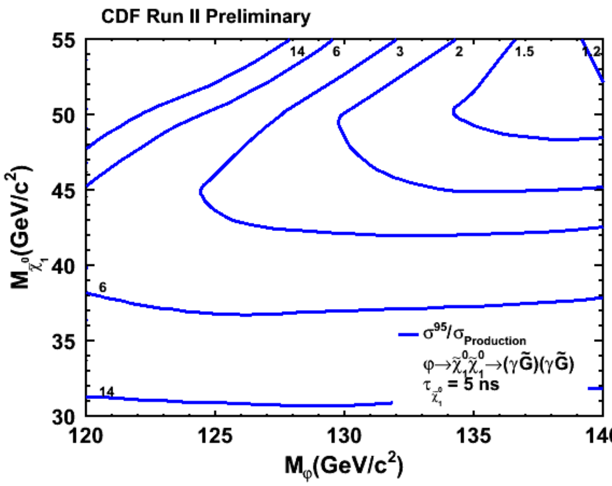


Fig. VI.1. A contour plot of the production cross section limit divided by the theoretical cross section. Note that we are not sensitive to regions with this ratio greater than one, and are sensitive to regions with below one. A version with larger masses is in progress.

parameters the lifetime and the neutralino mass to the most favorable combination as functions of the Phi mass and assess the sensitivity. Figure VI.2 is this result and shows us that we've been trying to use this analysis on completely the wrong region.

Our analysis turns out to be quite sensitive to high mass neutral scalars, which is a very good thing. This means that our benchmark point that we had been referencing at 125 GeV is in fact a poor choice and that a new benchmark of 200 GeV is a much more stable and promising benchmark. With this analysis starting before the discovery of the Higgs it was a good assumption then to be focused around 125GeV, but now with the Higgs discovered this analysis should refocus, to in fact regions that we are quite sensitive. This result is very promising and could even provide a large exclusion region for the values of the φ mass, $\tilde{\chi}_1^0$ mass, and $\tilde{\chi}_1^0$ lifetime.

VI.2 Looking Forward

As we seek to wrap up this analysis, we must move to the final results with the full data set and finish the validations of the acceptances at the new benchmark. What we have shown by walking

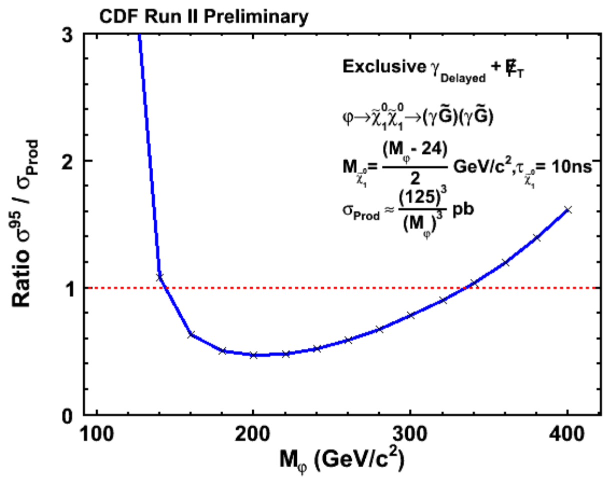


Fig. VI.2. The ratio of the expected σ^{95} to the production cross section as a function of the phi mass. Note that we have picked the optimal neutralino lifetime and relationship between the n$\widetilde{\chi}_1^0$ and φ mass. All the φ masses below the red dashed line (150- 350) are expected to be excluded.

through what the results look like with the partial sample is that we can set cross section limits on the production as a function of the three model parameters, and that they are quite promising. Though our limits shown in this thesis are only preliminary, we expect them to model the final results quite closely. If this proves to be true we may be able to set the first exclusion regions of their kind using photon timing and show that our analysis has the world's best sensitivity to this rare production.

This analysis has been in the works for a long time and even though we have found no evidence for new physics we may still have a result that pays off. Setting exclusion regions is an extremely important part of particle physics research and why it takes so many different analyses and collaborations to hopefully one day find evidence of something new. We are looking forward in this analysis to hopefully leave our contribution to the search for new particles at CDF as an exclusion region found with our unique and never before done method of photon timing and $\gamma_{\text{delayed}} + \not{E}_T$ final state.

I would like to acknowledge Dave Toback for his continued support and mentoring through this whole process. I can't imagine a better PI or mentor. He has been so supportive and eager to help me grow as a person and as a researcher. Dave's instruction has made me able to do and go places I couldn't have imagined were possible. His devotion to his students and their futures is truly way beyond what is required of professors. The way that he has incorporated me and other undergraduates into high caliber research so early in our education has been crucial to the success we have had. I am so inspired by example he has set as a professor and as a researcher that I have decided to follow the path same into academia. I can only hope that one day I can be the kind of mentor and advisor that he has been for me.I would like to acknowledge Dave Toback for his continued support and mentoring through this whole process. I can't imagine a better PI or mentor. He has been so supportive and eager to help me grow as a person and as a researcher. Dave's instruction has made me able to do and go places I couldn't have imagined were possible. His devotion to his students and their futures is truly way beyond what is required of professors. The way that he has incorporated me and other undergraduates into high caliber research so early in our education has been crucial to the success we have had. I am so inspired by example he has set as a professor and as a researcher that I have decided to follow the path same into academia. I can only hope that one day I can be the kind of mentor and advisor that he has been for me.

REFERENCES

[1] Y. Fukuda et al. *Phys. Rev. Lett. 81*, 1562, 1998.

[2] S. Martin (1997). arXiv:hep-ph/9709356. 6, 2011.

[3] Particle Data Group S. Eidelman et al. Review of Particle Physics. *Phys. Lett. B*, 592, July 2004.

[4] S. Martin. A Supersymmetry Primer. *arXiv:hep-ph/9709356*, 2006.

[5] M. Goncharov et al. Nuclear Instrument Methodes. *A565, 543*, 2006.

[6] Beringer et al. (PDG). *Phys. Rev. D 86 010001*, 2012.

[7] Ambrosanio et al. Search for supersymmetry with a light gravitino at the Fermilab tevatron and CERN LEP colliders. *Phys. Rev. D*, 54, November 1996.

[8] J. D. Mason D. E. Morrissey and D. Poland. *Phys. Rev. D 80, 115015*, 2009.

[9] P. Wagner and D. Toback. Prospects of searches for neutral, long-lived particles that decay to photons using timing at CDF. *Phys. Rev. D*, 70, December 2004.

[10] T. Aaltonen et al. (CDF Collaboration). *Phys. Rev. D 82, 052005*, 2004.

[11] Fermilab Beames Division. Run II Handbook (1998). *http://www-bd.fnal.gov/runII/index.html (accessed 2007)*.

[12] D. Acosta et al. (CDF Collaboration). Phys. Rev. D 71 032001. 2005.

[13] Tevatron Accelerator Division. Operations Rookie Books. *http://www-bdnew.fnal.gov/operations/rookie books/rbooks.html (accessed 2007)*.

[14] Fermilab Visual Media Services. *Graphic Arts Gallery, http://www-visualmedia.fnal.gov*.

[15] CDF Pictures Database. *http://www-cdf.fnal.gov/events/pics.html*.

[16] R.Blair et al. (CDF Collaboration). Fermilab Report FERMILAB-PUB-96-390- E. 1996.

[17] Z. Hong and D. Toback. Prospects for measuring the Neutralino Mass in GMSB SUSY decays of a Higgs Boson at CDF. *JHEP09 041*, 2013.

[18] A. Aurisano. Search for New Physics in the Exclusive Delayed gamma plus MET Final State in ppbar Collisions at sqrt(s)=1.96 TeV (Ph. D. Dissertation. 2012.

[19] D. Toback et al. (CDF Collaboration). *Phys.Rev.D 78 032015*, 2008.

[20] (CDF Collaboration) D. Toback, Z. Hong, et al. *Phys. Rev. D 88, 031103(R)*, 2013.

[21] J. D. Mason and D. Toback. Prospects for Searches for Gauge Mediated Supersymmetry with h0 -¿ 01 01 production in the Time Delayed Photon + MET Final State at the Tevatron. *PLB 702(2011)*, 2011.